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Fractal geometry analysis methods, analytical modeling and several experimental diagnostics were applied to an experimental reacting flow in a two-dimensional subsonic windtunnel with a backward facing step and provision for injection of inerts and combustibles through the porous floor behind the step. Experiments used laser velocimetry and Raman spectroscopy measurements for two components of the mean and fluctuating velocity and the local nitrogen concentration, which was found in this flow to be an accurate temperature sensor. The fuel used was hydrogen diluted with argon or nitrogen.

Fractal geometry yielded a new nonlinear adaptive filter and an interpolation method for improving the statistics of sparsely separated data points. Analytical modeling was improved over that from a prior program, and a two equation turbulent model now reproduces many of the observed features of the reacting flow.

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AFOSR FINAL REPORT

FRACTAL IMAGE COMPRESSION OF RAYLEIGH, RAMAN, LIF AND LDV DATA IN TURBULENT REACTING FLOWS

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SUMMARY

Analytical modelling, new fractal-based methods of data analysis and several experimental diagnostics were applied to an experimental flow in a two-dimensional windtunnel with a backward facing step and provision for the injection of inerts and combustibles through the porous floor behind the step. Laser-based diagnostics for velocity, species concentration and temperature measurements included LDV and Raman spectroscopy, augmented by some intrusive temperature measurements for validation of results. Two fractal based methods of data analysis were developed, one to improve signal to noise ratio and the other to provide better certainty in the experimental data when confronted by temporally sparse data points. Analytical modelling techniques were based upon a two equation model of turbulence, Favre averaging being incorporated to account for variable density effects. The hot flows used hydrogen-argon and hydrogen-nitrogen mixtures as the fuel injectant.

Major findings were a) the invention of a fractal filter, b) the development of a fractal interpolation technique for data augmentation, c) the discovery of extreme analysis sensitivity of the shear layer flame location to the fuel flow, d) the failure of the analysis method to yield as accurate results for the hot flow as had been found in cold flow (nevertheless yielding the gross features of the hot flow), e) the discovery that in this flow the Raman signal is primarily a temperature sensor, and f) the development of a unique method of data reduction for the Raman signal in the face of severe glare in the windtunnel. An additional year on the program was requested to complete joint measurements of temperature and velocity and further turbulence modelling with fractal based methods of data reduction as well as to complete the LIF measurements on OH concentration.

RESEARCH OBJECTIVES

The primary objective was to determine the limits of scientific understanding and predictability of a particular complex turbulent reacting flow. This flow field models that in the flame stabilization region of a solid fueled ramjet. Secondary objectives included a) the development of several laser diagnostic methods operating under particularly severe conditions of signal to noise ratio, b) the development of fractal based methods of data analysis to aid in item a) and c) the determination of necessary modifications to the turbulence model to affect agreement between theory and experiment.

ACCOMPLISHMENTS

Facility

The facility used in this study is described in Ref. A, in the REFERENCES AND PUBLICATIONS section of this report. The combustion windtunnel is a two-dimensional, backward facing step facility with the provision for injection of inerts and combustibles through a porous floor behind the step. Injectants used were mixtures of hydrogen-argon and hydrogen-nitrogen. The facility was developed during the forerunner of this program under Contract No. AFOSR-83-0356, entitled "Heterogeneous Diffusion Flame Stabilization". The facility simulates the flame stabilization region in a solid fueled ramjet. For scientific purposes, however, it was used as an experimental device to investigate a highly complex, turbulent, recirculatory reacting flow with mass addition and combustion.

Experimental Effort

Following publication of the final cold flow, foreign gas injection results in Ref. B, full effort was turned to the investigation of the flow field with combustion. Velocity distributions were measured using laser Doppler velocimetry and temperature distributions were determined using Raman spectroscopy. Hydrogen was used exclusively for the fuel so that soot radiation and other species would not contaminate the Raman measurement, which concentrated on the species nitrogen. The fuel injection rate is relatively low, 1.82×10^{-3} and 5.4×10^{-3} lb/sec of H_2 and diluent, respectively, in accord with solid fuel ramjet fuel pyrolysis rates.

The horizontal and vertical components of velocity were mapped by LDV for both the cold and hot flows, showing a significant difference between the two, both in the mean and fluctuating components. The correlation between the vertical velocity fluctuation and the Raman measurement would show the mass and heat transfer in the vertical direction, to be compared with analysis. However, time ran out on this program before these simultaneous measurements could be made. Reference C documents the results of the Raman and LDV measurements.

The development and use of the Raman system in this configuration represented a non-trivial task. The windtunnel has glare-producing walls and the beam must be directed through quartz windows, which cause some window fluorescence. These problems add severe noise to the measurement as compared to measurements made by other investigators on open flames. The ultimate goal was to develop the system to the point where simultaneous Raman-vertical velocity measurements (both mean and fluctuating) could be made. This would provide species concentration, temperature, and turbulent heat and mass transport measurements to be compared to the analytical modelling results.

The Raman system consists of a linear flashlamp pumped pulsed dye laser capable of ten shots per second. This produces data points separated far enough that they are uncorrelated with one another. That is, they are sparse data points requiring long run times to obtain statistically significant pdf's for data analysis. Knowing this in advance was one reason for entering the fractal image compression methods, discussed below.

Following system development, the Raman signal was mapped throughout the flow field. In order to determine the effect of the bleed gas upon the N_2 concentration, both Argon and Nitrogen were used as fuel diluents. Little difference was found between the two cases, indicating that the bleed gas addition was too small to affect the Nitrogen concentration in the test section. This permits the Nitrogen concentration measurements to be used to determine the local temperature, except very near the wall. This is, of course, only true if local chemical equilibrium is obtained (fast kinetics) and nearly unity turbulent Lewis number occurs for the main species in the flow. Thermocouple traverses showed equality with the temperature (density) deduced from the Raman measurements, so that at once concentration and temperature are being measured.

Reduction of the data proved nontrivial because of glare and window fluorescence. A novel method was developed to remove the resulting noise from the Raman signal. The flow was turned off and the upstream and downstream sections of the windtunnel were blocked off. The test section was then loaded with Argon by bleeding the gas through the porous floor. A reading of the Raman signal (theoretically zero, but nonzero because of noise) was made throughout the tunnel. This local noise was then subtracted from the hot flow signal at every point in order to deduce the true N_2 concentration. This is the first known time that such a calibration has been demonstrated.

Analytical Effort

a. Fractal Geometry

References D-F document the progress in using fractal geometry in data analysis during the course of this program. First of all a fractal filter was developed. This nonlinear adaptive filter monitors the local fractal dimension of a time series and will adjust its strength in accordance with the prevailing fractal dimension. This invention was a byproduct of the program and is applicable to time series analysis in general. It should be of general interest to many practitioners of turbulent combustion data analysis. It was applied to previously obtained Rayleigh scattering data, which were contaminated by photomultiplier Shot noise of a higher fractal dimension than the true signal. The fractal filter was used to clean these data.

Also of direct interest to this program was the development of fractal interpolation techniques to increase the confidence in the statistics of the pdf's generated. It was found for widely separated (but still correlated) data points a fractal interpolant could generate data points in between the sparse points that could be justifiably considered "real" data. The technique was originally intended to be used on the Raman data. However, because of the low laser repetition rate neighboring data points were uncorrelated and simple interpolation was, therefore, not possible. However, it is likely that another technique, hidden variable fractal interpolation, which is currently being developed will be applicable to the analysis of the joint Raman-LDV data once they have been obtained. This is a three-dimensional interpolation method which may work if one of the time series is well represented (LDV) while the other (Raman) is sparse. A crucial assumption in the application of this method is that the two traces being worked with have approximately the same fractal dimension. It is the experience of the PI's that this is often true in turbulence at high Reynolds number, but it must be independently checked. Preliminary work on this technique was completed but must await the joint data for application.

b) Analytical Modelling

References G-I were published during this effort, but document the results obtained during the prior contract. At the beginning of this contract, the two equation turbulence modelling had progressed to the hot flow case including the effects of temperature fluctuations and finite rate reactions. However, the bleed section did not include the effects of diluent, nor did it include the effects of an inert injection section downstream of the fuel injection region used in the experimental setup for tunnel wall cooling. In the absence of the diluent flow the model predicted a flame lying on the floor of the tunnel, which was not what was experimentally observed. Moreover, the original analysis showed a shortening of the reattachment zone with combustion while the experiment showed a lengthening.

During this program the above deficiencies were corrected. The grid in the vicinity of reattachment was tightened. As a result the lengthening of the reattachment zone with combustion is now predicted. A more detailed modeling of the diluent and cooling gas flows moved the flame off the floor into the shear layer. Nevertheless, the flame position is extremely sensitive to the fuel flow rate. While gross features of the flow are now well predicted by the model the mixing rates are still over-predicted so that the flame is still too close to the floor. The last deficiency was being investigated at the end of the program and will be addressed during the one-year follow-on. Suspicions are that either the temperature fluctuation effect (not used in the most recent calculations) may be responsible or that a new model is needed for the pressure-velocity correlation in the turbulent kinetic energy equation.

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OTHER INTERACTIONS AND PRESENTATIONS

A. Presentations at three AFOSR Contractors' Meetings, 1988-1990

B. Strahle, W.C., "Application of fractal geometry in turbulent combustion," Invited seminar at University of Arizona, March, 1989

C. Strahle, W.C., "Application of fractal geometry in turbulent combustion," Invited seminar at Kimberly-Clark, Atlanta, GA, October, 1989

D. Strahle, W.C., "Application of fractal geometry in turbulent combustion," Invited seminar at Georgia Tech Center for Nonlinear Dynamics, November, 1989

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Students Graduated

Dr. Fang-Hei Tsau, Ph.D., May 1988

Mr. Donald Kenzakowski, M.S., September, 1989

Mr. John Szillat, M.S., September, 1990

AWARDS

No new awards.

AFOSR PROGRAM MANAGER INFORMATION

The program was given one more year to finish the work delineated above. The fractal filter attracted international attention; no patent was deemed required since it was a computer program and published in the public domain.